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Dermitzakis, Konstantinos ; Arieta, Alejandro Hernandez

Originally published at:
Dermitzakis, Konstantinos; Arieta, Alejandro Hernandez (2009). Anthropomimetic approach to the design of a prosthetic robot hand. In: Workshop on Understanding the Human Hand for Advancing Robotic Manipulation, Robotics Science and Systems Conference, Seattle, WA, 28 June 2009 - 1 July 2009.

Anthropomimetic approach to the design of a prosthetic robot hand

Konstantinos Dermitzakis and Alejandro Hernandez–Arieta

Artificial Intelligence Laboratory, University of Zurich, Switzerland
dermitza@ifi.uzh.ch

A loss of a limb is a common phenomenon among both humans and animals. Where animals have to cope with such a loss, humans have pushed attempts towards limb replacements for quite a long time. It has only been relatively recently that such devices, in addition to providing a cosmetic replacement can also be sophisticated enough to account for some of the functions of the lost limb. Upper-limb replacements in particular are inherently difficult to realize as the human hand is the most complex and important tool man possesses.

The prosthetics and robotics research fields have marked increasing progress towards functional hand replacements. By satisfying requirements such as (1) numerous sensory modalities, (2) high processing capabilities, and (3) high output torque, current robotic/prosthetic prototypes are close to attaining functionalities similar to those of the human hand (Balasubramanian et al., 2008). In the prosthetics industry however, such advancements are usually not realized. Upper limb prostheses used in the real world pose additional, inherent requirements which are usually not taken into consideration by robot designers. Such requirements, vital to the adoption of the prosthetic device by its user (Carrozza et al., 2006), are: (1) reduced power consumption, (2) low device weight, (3) high dexterity, and (4) ease of use. In contrast, prosthetics research is carried out using robotic hand prototypes that only partially fulfill the above requirements. Even so, most prosthetic – and arguably robotic – hand prototypes cannot be considered optimal. Size and weight considerations are rarely taken into account, and power consumption issues are usually not dealt with; when they are, usual approaches involve either smaller or fewer motors, disregarding any dexterity requirements.

Clearly, for upper-limb amputees to directly benefit from prosthetics research, the devices being used to conduct this research should themselves adhere to these real world requirements. Had the biomechanics of the human hand been taken into consideration, could such requirements be met in a better fashion than traditional engineering approaches? We argue that by studying the morphology of the human hand, we can identify and exploit principles that underlie its functions, creating a device that can be of use to patients in real world circumstances.

Towards identifying the underlying functional principles of the human hand, we focus our attention on two important properties: (1) the phalangeal curvature and (2) the friction between tendons and their sheathing under high loads. Even though both properties have been well documented in the anthropological and medical fields, to our knowledge, they have not yet been exploited in robotics.

The human finger consists of three segments or phalanges, the distal, middle and proximal and a palm segment, the metacarpal. All of the above segments are so similar in morphology that further discussion will include the metacarpal segment. Despite the many evolutionary changes the human finger has undergone, a characteristic that is common to numerous arboreal creatures is the curvature of the finger segments. Such phalangeal curvature is discussed in paleontology and primate morphology, where the association between this curvature and arboreality has been extensively documented (Richmond et al., 2003; Stern et al., 1995). Arboreality itself however is not a direct indicator of the reasons behind such a curved finger structure despite the fact that most arboreal creatures possess it. A recent study has identified, using finite element methods, the benefits of this morphology (Richmond, 2007). The results from this study indicate that a curved bone segment like the one present in siamang mammals – but also humans – can provide significant strain benefits over a similar but non-curved segment. The strain present on the curved segment is roughly half that of the straight one, despite equivalence in lengths, areas, mechanical properties and loading force conditions in the two models. This difference in strains can be attributed to the higher compression forces present in the curved model. Such a result is quite important in prosthetics research as it indicates that a curved finger segment with less volume than a straight segment will in fact withstand the same strain with the same loading forces present. A decrease in bone volume will be beneficial in at least two ways. (1) Given a constant bone density, the weight of the device scales with its volume, satisfying the according requirement. (2) We can identify a volume metric demonstrating that a minimal bone volume is preferred. The empty volume gained can be efficiently employed by other structures such as a cosmetic skin or a large volume of sensory modalities – presently absent from most prosthetic hands in use – whilst maintaining the same weight as a device with a larger bone volume.

A simple curved bone segment was created in Solidworks©. The curvature of the bone segment is identified by a radius R of a circle tangent to the segment's joints, denoted by two smaller circles of radii R1 and R2. To design a complete robotic finger, the original segment was replicated, only changing its length and the diameters of the joints accordingly. Our initial model shows that when fully realized, a complete hand will provide sufficient structural strength to be used in every day activities while at the same time will help satisfy the weight constraints of the device.

The presence of friction in most mechanical devices is unwanted and usually associated with energetic losses. Such is also the case with all robotic and prosthetic hands to date, where hands employing a tendon-driven transmission mechanism aim towards frictionless transmission, e.g. by utilizing Teflon cables and sheaths. In the human tendon-sheath mechanisms however, frictional forces might be beneficial. It has been experimentally shown that during high-load flexion of the interphalangeal joints, eccentric and concentric forces differ by 9%, a difference that can be directly accounted to tendon-sheath friction (Schweizer et al., 2003). In addition, the property of tendons to compress when tensioned, but also the orientation of tendon and sheath fibers further simplify the appearance of frictional forces (Walbeehm et al., 1995). Such utilization of friction is present in a more specialized form in chiropterans (bats), which employ frictional forces to dangle on their fingers without the application of muscular force. Preliminary results on a robotic finger indicate a higher mechanical advantage of a frictional (rubber sheaths) tendon transmission system over a frictionless (Teflon sheaths) one during a pre-caging task. Utilizing a friction mechanism in robotic hands can have two alternative advantages: (1) finger force output under high loads could be increased at no motor cost; or (2) it could be achieved using smaller motors, thus saving both weight and energy.

Designing a human hand replacement cannot be treated as a purely engineering problem as is usually the case with prosthetic research prototypes. Embodiment is well known to lead to surprising insights (Pfeifer et al., 2007). And there is much to be gained by studying and exploiting the biomechanics of the human hand. We can extract principles and concepts that can be used towards advancing prosthetic research. In turn, we can realize devices that will directly benefit prosthesis users by better satisfying real use requirements. Our research aims at paving the way to exposing principles of the human hand morphology, and using them directly to implement prosthetic hands. Showcasing the benefits of this approach will highlight the fundamental importance of morphology not only of the hand but of the human body as a whole.

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